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Gamma Ray Pulsar Analysis from Photon Probability Maps

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Abstract

We present a new method of analyzing skymap-type γ-ray data. Each photon event is replaced by a probability distribution on the sky corresponding to the observing instrument's point spread function. The skymap produced by this process may be useful for source detection or identification. Most important, the use of these photon weights for pulsar analysis promises significant improvement over traditional techniques.

1 The Method

We have used the derived point spread function for the COS-B experiment to develop data analysis tools with improved ratios of signal to background with applications to source identification and searches for faint γ-ray pulsars. We generate a weighted photon probability map to enhance any significant γ-ray signal present in the data and suppress undesirable background fluctuations. The basis for this method can be formulated in two equivalent ways:

a) By definition, the point spread function (PSF) of an imaging instrument describes the redistribution of photons from a particular direction on the sky into the observed distribution. Thus, each event may be represented as a continuous distribution of event weights on the sky (for COS-B, the PSF vanishes for $\theta > 20°$).

b) Correspondingly, any location on the sky receives some weight from each γ-ray seen during the experiment. In other words, each observed photon has a certain probability, given by the PSF, to have originated at that location.

Based on this concept, we smooth each photon arrival direction into an extended probability map. When investigating a particular source location, our analysis includes *all* γ-ray events through their weights at that position. To demonstrate the usefulness of this approach we apply it to the light curve of the Crab pulsar. The extraction of a source list from our COS-B probability map is in progress.

2 COS-B Probability Maps

The observed direction of each photon event does not correspond directly to its point of origin on the sky. Information on the detector angular resolution is contained in the PSF of the detector. To identify γ-ray sources, the intrinsic fuzziness of γ-ray detectors can be included in the analysis by creating a skymap of "probability flux" rather than "photon count flux".

The weight of a γ-ray event with observed direction α for a small solid angle $\Delta\theta$ centered on a point p is defined as

$$w(p;\alpha) = PSFSR(\theta(\alpha,p))\Delta\theta,$$

where PSFSR is the point spread function per steradian. We use the PSFSR derived by the COS-B team using the Vela pulsar (Mayer-Hasselwander 1985).

The celestial γ-ray intensity, I_c, at a point on the sky (in terms of weight) is

$$I_c(p) = \frac{\Sigma_{\gamma's} w(p) - \int_{sky} d\Omega w(\Delta N_b(p))}{\int_{sky} d\Omega w(\Pi(p))} - I_b,$$

where the summations are taken over all events seen by the experiment, the $w(p)$'s are the weights of the individual events, $w(\Delta N_b(p))$ is the weight, at p, of the instrumental background correction for all other points on the sky, and $w(\Pi(p))$ is the weight, at p, of the exposure (in $cm^2\ s$) for all other points on the sky. I_b is the "standard" background correction as given by the COS-B team. The units of I_c are $photons/cm^2\ s\ sr$.

This defines our weighted sky intensity probability distribution. We have sampled this continuous map at .5° intervals for the whole sky. The resultant maps in the energy ranges 50-150 MeV, 150-300 MeV, and 300-5,000 MeV are shown in figure 1.

This technique may not be ideal for some aspects of *source identification.* It results in a skymap which may be "too fuzzy" since the photons are effectively convolved twice through the PSF. That is, they are spread once in passing through the detector and again by our technique. However, it does not make any arbitrary smoothing assumptions. A comparison of our source list (in progress) with those resulting from other techniques (e. g.Simpson & Mayer-Hasselwander 1987; Bloemen 1989) will be useful. For instance, our technique finds a possible source of high intensity but low statistical weight at $l = 309.5, b = -30.5$ in the middle energy range (see figure) it should be instructive to see if the maximum likelihood methods of Grenier et al. confirm this source candidate.

3 Lightcurve of the Crab Pulsar

For analysis of periodic sources, we analyze weights vs. phase instead of counts vs. phase. Superimposed on a background that is $\sim$ uniform in space and time, the γ-ray pulsar adds a signal that is localized both in space and time. Standard analysis of γ-ray phases considers all photons within a given acceptance cone equally. Photon arrival directions

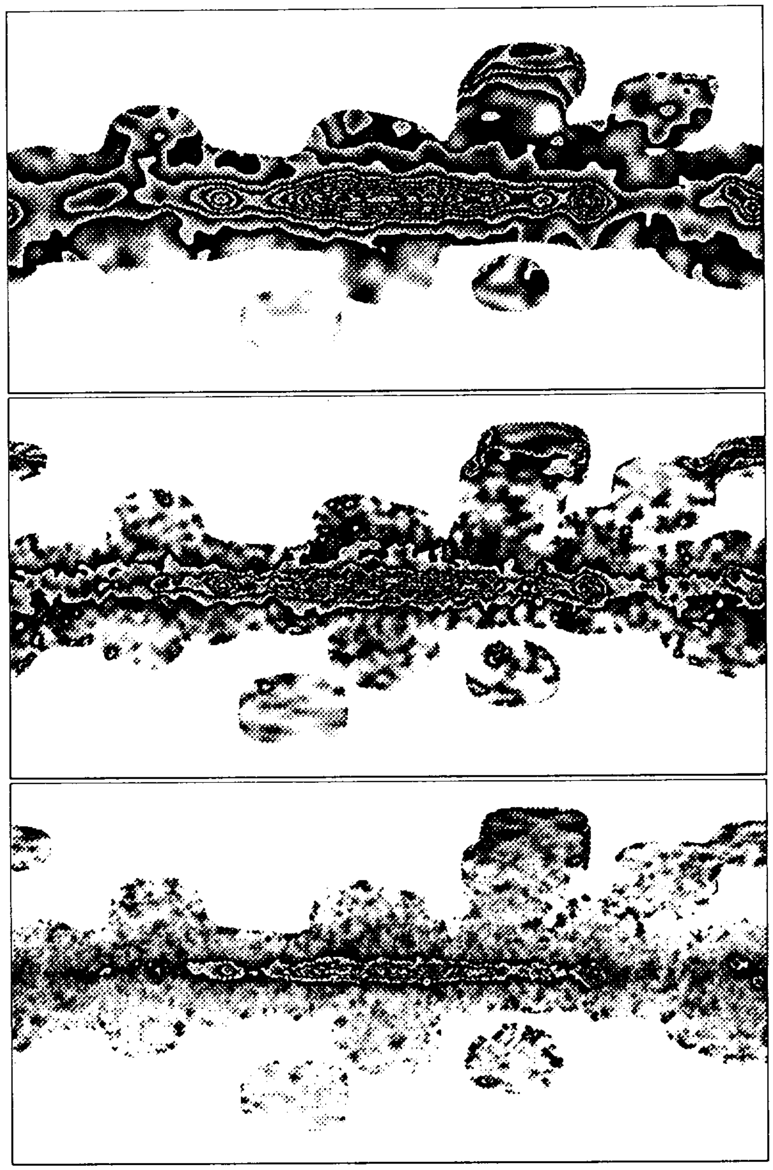

Figure 1: *Skymaps of photon weight of the COS-B observations for the energy ranges 50-150 MeV, 150-300 MeV, and 300-5,000 MeV. The photon weight distribution on the whole sky is sampled on a grid of .5 degree spacing. Since COS-B did not observe all areas of the sky, some regions of the map at high galactic latitudes are blank. The graymaps used here represent intensity of* photons/cm^2 s sr, *with intensity increasing from black to white. This graymap is wrapped around 10 times between the faintest and brightest spots for better monochrome resolution. It is, essentially a grayscale "contour map". The graymaps are assigned individually for each map (i. e. equal gray intensities on different maps do not represent equal photon fluxes).*

TABLE 1: Signal to background

Observation	Peak Signal (Std. Dev.)		Integrated Signal (Std. Dev.)	
	weights	counts	weights	counts
Crab Pulsar	43	18	176	101
1/2 Crab Pulsar	33	12	107	59

closer to the pulsar position have a higher probability of containing the sought after pulsed signal. Thus, by considering both space and time, we gain an added degree of freedom for extracting the signal from the background.

The standard binning technique folds solar barycentric arrival times with the measured period characteristics obtained from radio observations (Buccheri et al. 1983). Traditionally, one defines an acceptance cone around the source direction with opening angle

$$\theta_{max} = 12.5E(MeV)^{-.16}.$$

Inside this cone, all photons contribute equally to the light curve. In our approach, PSF weighting implicitly performs this task; thus, we can utilize the maximum aperture consistent with a non-zero PSF ($\theta_{max} = 20°$ for COS-B).

Then, instead of binning counts by phase to create a light curve histogram, we bin weights by phase. Results for the two methods for the Crab Pulsar are shown in our figure 2.

Figure 3 highlights the differences between the two approaches. Essentially, the traditional method uses a uniform probability function inside an acceptance cone that has an energy dependent width. We have used, instead, a probability function which extends over the full range of non-zero PSF, but binned into 3 energy ranges. This binning follows COS-B tradition, could easily be made finer.

To allow direct comparison of the two methods, we plot the standard deviation for each bin. To calculate the average background level, we have used the "flat" portion of the Crab pulsar's γ-ray light curve between the second peak and the end of the period. The resulting plot shows counts (weights) minus average background divided by standard deviation from background. We show results for all, and half of the Crab pulsar observations of COS-B to demonstrate the performance of this technique for reduced sampling times. The results in terms of maximum signal above background and total integrated signal are given in table 1. While the exact numbers are dependent on bin size, the improvement is dramatic in all cases.

This obvious increase in significance of detected pulses should also benefit the cluster analysis algorithm of Buccheri, et al. (1988). We are currently investigating this and other extensions to the general weighting technique.

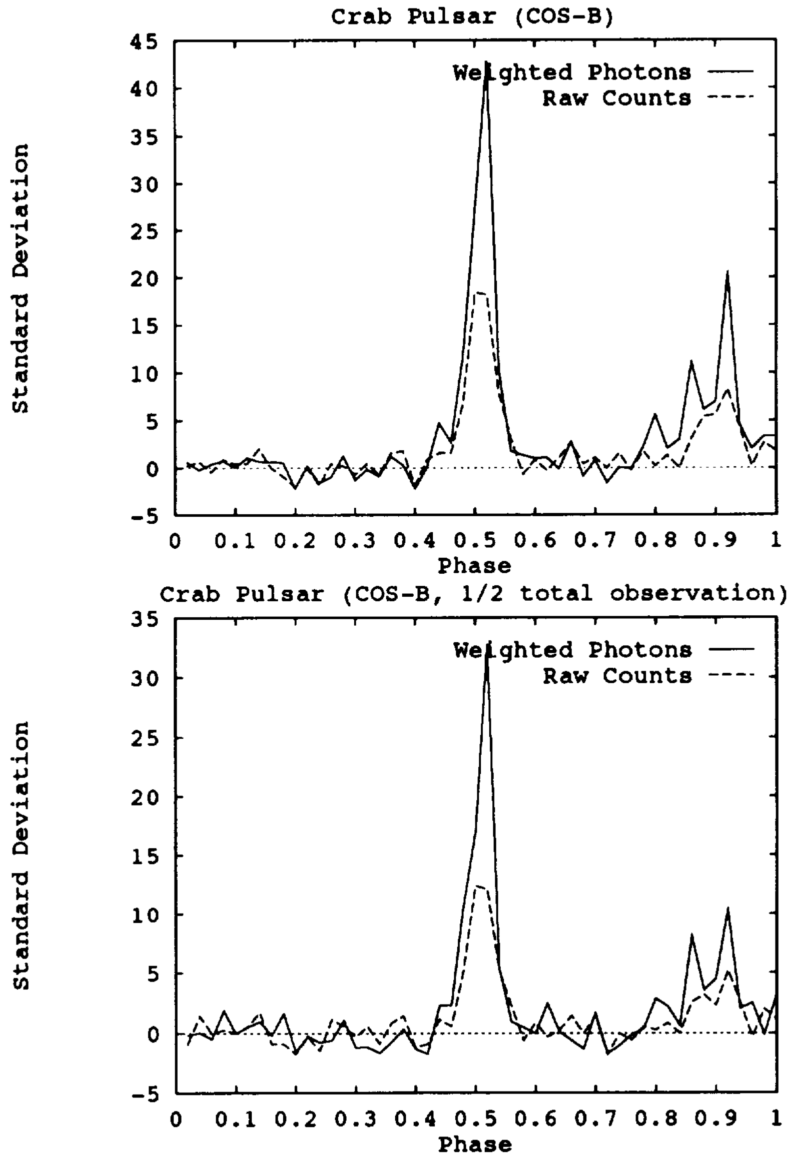

Figure 2: *Shown are the weighted photon method (solid) and the standard count method (dashed) of phase binning for the full COS-B data set for the Crab pulsar. Note the dramatically improved signal for the weighted photon method. (Number of bins = 50.)*

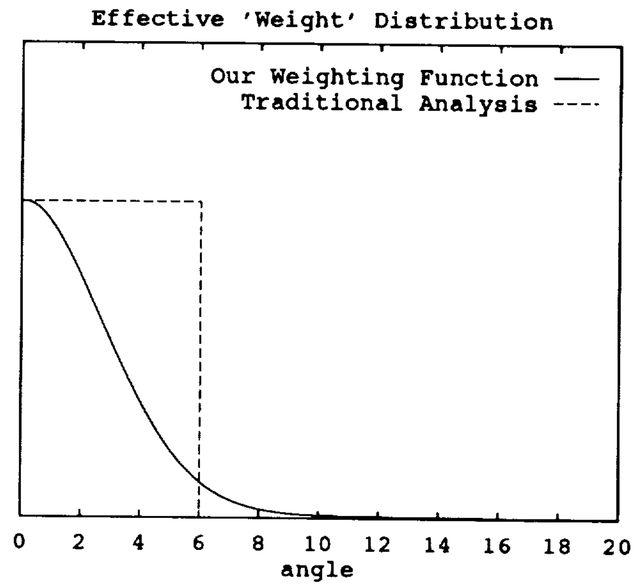

Figure 3: *Schematic drawing comparing the effective probability "weight" distribution for traditional pulsar analysis (dashed) and our weighting function (solid) for a given energy* ($\sim 100 MeV$).

Acknowledgements

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